CHAPTER 15

Structural Vulnerability

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CHAPTER 15

Structural Vulnerability

Introduction

1 Structural vulnerability is associated with the ability or otherwise of structure to resist weapon effects. In the majority of current ships, and indeed since it became impracticable to fit armour to more than the most local areas of a ship, structure has not been designed with reduced vulnerability in view, although the layout is usually arranged to minimise the vulnerability of critical compartments. Current thinking is that it may be possible to rearrange structure so as to reduce vulnerability markedly without an unacceptable increase in weight. These ideas are however in the early stages of development and are not validated, so it is not yet reasonable to present them. Nevertheless, there are a number of factors which the designer should have in mind when developing structural arrangements which may significantly improve the resistance of the ship to weapon effects.

2 To put these factors into context, it is first necessary to discuss the damaging mechanisms of major weapons, and then how the effect of these mechanisms may be minimised or contained.

Types of Attack

3 Attacks may be from above or below water and the effects of each are markedly different. In either case the weapon can detonate on or following impact, or at a stand-off using a proximity fuse. In the underwater case penetration following impact is likely to be very limited as the velocity of the weapon is low, and damage is therefore restricted to the vicinity of the impact point. Frequently, greater damage can be done underwater from a stand-off explosion which can cause extensive shock damage over a large part of the vessel, and may also damage the primary structure through whipping.

4 Conversely, above water attacks are at high velocity and the weapon may penetrate far into the hull before detonating, causing a very large volume of damage, while a stand-off weapon in air will only generally shower the target with fragments (except for fuel-air explosives as described below). Thus, the means of resisting above and below water attacks are very different.

Above Water Weapon Effects

5 These weapons include bullets, shells, unguided rockets, bombs and guided missiles. Bullets, typically 7.62 mm and 0.5″, are either ball or armour piercing (AP). The ball type

consists of a lead or mild steel core covered with a soft metal jacket. AP bullets have a hardened steel core. Depending on the striking velocity and angle of impact, AP bullets can penetrate thin structural steel plates. Shells usually of 20 mm calibre and upwards, are similar to bullets except that they carry, in addition, charges of high explosive (HE) or HE/incendiary mixtures. Shell casings require to be sufficiently thick to withstand explosive discharge and high acceleration so that the proportion of HE charge weight is 10% at most. This limits blast damage, so damage is mainly from fragmentation. Heat from the explosion can cause fire. Guns fitted on present day ships, for example 4.5″ Mk 8, are mainly for shore bombardment using HE shells. Unguided rockets, delivered by aircraft, can be an effective weapon. WWII rockets were typically 2″ HE (having a charge of about 0.5 kg of HE), solid AP, or with a shaped anti-tank charge.

6 As was shown during the Falklands War, bombs can be very effective against ship targets if accurately delivered. Bombs used for attacking ships would probably be general purpose (GP) HE bombs of medium capacity (MC), typically of 250 or 500 kg. The charge-to-weight ratio is higher than for shells, say 75% for high capacity (HC) and 50% for MC. Depending on the height and angle of drop, these bombs can penetrate a considerable thickness of steel. AP or semi-armour-piercing (SAP) bombs have also been used against heavily armoured ships.

7 Guided missiles fired from other ships, submarines or aircraft are the most likely above water threat. These range from small helicopter carried weapons with warheads of around 10 kg, to large ship carried weapons with up to a tonne of HE in the warhead. For use against ships the warheads are generally SAP to enable the warhead to enter the ship before exploding, but in consequence have a smaller charge weight; to penetrate well protected compartments a shaped charge head may be used.

8 High explosive weapons may have sufficient casing strength to penetrate unarmoured ships and explode internally. They may also be fused to explode before contact, on contact, or after penetration. Damage is caused by heat, airblast, fragmentation or a combination of these effects. High explosive materials, when detonated, convert from solid to gas in a few hundred microseconds, creating extremely high temperatures and pressures within the weapon. Typical values are 5000°C at 21,000 kPa.

9 When a fuse is activated it detonates a highly sensitive explosive known as the primer or exploder. This initiates the explosion of the main charge of less sensitive explosive. A detonation wave spreads through the main charge at speeds of up to 9000 m/s. In front of the wave the explosive is unchanged. Behind the wave the explosive is completely changed into gas and is commencing to expand. The enormous pressures rupture the weapon casing into numerous fragments and produce the following:

a. A fireball or flame front of expanding gas at a temperature of thousands of degrees Celsius.

b. An air-pressure shock or blast wave radiating from the explosion at many times sonic speed.

c. Physical movement of the surrounding air.

d. Outward projection of casing fragments at thousands of metres per second.

e. Projection at lower velocities of larger parts of the weapon, for example from the guidance and propulsion units (kinetic energy effects).

f. High overpressures of long duration in confined spaces.

g. Large quantities of smoke.

10 The fireball is the hot mass of compressed gas formed by the explosive reaction. Its extremely high temperatures are shown initially as a flash. These high temperatures are, however, dissipated within a relatively small volume compared with the effects of blast and fragmentation. Materials near the centre of the explosion will burst into flames, melt or vaporise. Radiant heat may ignite or pyrolyse nearby objects. Any remaining fuel and oxidants within a guided missile's propulsion system will ignite and enhance the fire, and smoke will result from the explosion products and from heated materials. The radiant heat may weaken the structure thereby reducing its resistance to the blast. Note that steel begins to lose strength at temperatures above 450°C, and other structural materials at much lower temperatures (see Chapter 5).

11 The rapid expansion of the fireball accelerates the air ahead of it at many times sonic speed, creating a sonic shock wave. Shock is used here in an aerodynamic sense and the term blast is more usual when discussing the effects of an explosion. The blast wave consists of a very thin layer of compressed air which radiates from the centre of the explosion in a roughly spherical manner. The pressure in the blast wave reduces with distance and the speed reduces to the speed of sound as the pressure falls to ambient. The blast wave must be considered in greater depth to understand its damaging effects; it comprises the following:

a. An instantaneous pressure rise in the blast front. This is known as the peak static overpressure. The pressure drops to zero overpressure fairly quickly behind the front, that is from milliseconds to a tenth of a second for a large bomb.

b. A dynamic pressure. The shock wave causes the air behind it to be accelerated outward. The speed of the air drops quickly as the pressure drops. This air movement causes aerodynamic drag and is very effective in causing damage.

c. A negative phase which follows the overpressure. Its duration is several times longer than that of overpressure but the pressure is not far below atmospheric.

Means of predicting these pressures are discussed in Chapter 4.

12 When the blast wave strikes an object, reflection can cause the static pressure to increase up to 15 or even 20 times. The dynamic pressure is also increased but to a lesser degree. Blast reflection within a compartment can be repeated many times, thus increasing the damaging effects. The blast is affected considerably by the thickness of the weapon's casing; expenditure of energy in breaking up the casing and projecting fragments reduces the intensity of the blast. Because of the variations between weapons it is usually necessary to define an equivalent TNT bare charge weight when considering blast effects.

13 The cases of shells and bombs are thicker and stronger at the ends than along the cylindrical body. When explosion occurs, the cylindrical body is expanded and shattered into fragments which are propelled nearly normal to the cylindrical surface. These fragments are called the side spray. The exact direction depends on whether the fuse initiates the explosion at the nose or the tail. If initiated at the nose the main zone of fragmentation is displaced away from the nose by 90° to 120° from the forward direction. For tail initiation it is displaced forward by 45° to 90°. The velocity of the weapon before explosion must be added vectorially, displacing the side spray further forward and increasing the fragment velocities. Casings can be designed to give fragments of predetermined size with a limited degree of success, and the explosive charge can be shaped to give predefined 'self-forging' or 'controlled' fragments. Otherwise, fragments vary considerably in size and velocity; the initial velocity of fragments is very high and depends upon the ratio of charge weight to casing weight. For a light casing typical velocities are between 2100 and 3300 m/s and for heavier fragmentation type weapons they are lower, typically from 750 to 1500 m/s.

14 In addition to the damage from heat, blast and fragments, the large quantities of gas generated by the detonation of high explosives produces an overpressure in confined spaces which will rupture relatively light steel structures such as are used in frigates and smaller vessels. Unlike blast pressure, this overpressure is of comparatively long duration. Venting arrangements in magazines are fitted so as to minimise the excessive overpressure that may occur from the detonation or deflagration (rapid burning) of a ship's own weapons caused, for example, by bullets or fragments striking a warhead.

15 Fuel-air explosive (FAE) weapons contain a type of explosive which causes damage by detonating an aerosol cloud of a fuel-air mixture. High blast pressures can be produced which are of long duration compared with that of conventional high explosives. The destructive capability is several times that of a comparable weight of HE. Damage is principally caused by the ship's ventilation system ingesting the fireball resulting from the explosion with consequent heat and fire being spread extensively through the ship. Additionally, heat and blast damage will be caused to weapons and sensors and to vulnerable upper deck equipment.

16 Nuclear weapons, in addition to producing blast, also create a very large heat and radiation fluxes as well as various electromagnetic and electrostatic effects. These are all described in some detail by Glasstone and Dolan (1977), but only the blast and heat flow are of direct relevance to the structure.

Underwater Weapon Effects

17 Underwater weapons consist of torpedoes and mines, although near-miss bombs exploding under water may produce similar effects. Anti-surface ship heavyweight torpedoes can carry the equivalent of 460 kg of TNT, while lightweight torpedoes carrying about 140 kg of TNT equivalent can also be effective against surface ships if accurately positioned. Mines also have a large HE content. Both weapons have been greatly advanced since WWII and some can be activated by ship signatures to seek out a target and explode in close proximity.

18 Underwater weapons, usually exploded close to the hull, produce damage by shock and whipping. The shock may damage equipment, machinery and personnel or cause distortion or rupture of the hull if it is sufficiently severe. Whipping is resonant vibration of the hull girder at high amplitude and may buckle the deck or bottom structure or even break the back of the ship. Explosions in contact with the hull, as many were in WWII, will produce hull rupture and internal explosion effects to some degree, including fire and blast.

19 Underwater weapons are lightly cased to obtain maximum energy transfer to the water. The HE converts from solid to gas in the same way as in surface weapons but the enormous pressure causes a spheroidal shock wave in the water. This is a pressure wave consisting of a virtually instantaneous pressure rise followed by a nearly exponential pressure decay. The negative pressure phase is negligible. The peak pressures are greater than they would be in air and decay at a lower rate. The velocity of the shock wave is about five times that of an air blast wave. The explosion gases form a bubble which can cause additional damage if beneath or close to the hull. This gas bubble expands and contracts for several oscillations, emitting further shock pulses when near its minimum size. These shock pulses decrease in magnitude and even the first bubble pulse, when the bubble is at its first minimum size, is fairly weak compared to the original pressure pulse. Typically, the peak pressure in the first bubble pulse is 10% of the main pulse but its time constant is 10 times or more, resulting in an impulse comparable with or greater than the impulse from the main shock wave.

20 As the bubble collapses it is unstable and may not reduce to a spherical shape, but may divide into a number of smaller bubbles which can join together at the next expansion. Because of buoyancy the bubble rises at high speed and this enhances its damaging effect when beneath or close to the side of the ship. Another feature of bubble behaviour is its attraction to rigid surfaces. A rigid surface exerts a weak repulsion when the bubble is expanding but when the bubble is contracting it has a strong attraction. The overall effect is that the bubble will move towards a surface such as a ship's hull and remain there if contact is established, usually causing heavy damage. If, however, the attacking weapon explodes on the sea bed, the sea bed will tend to attract the resulting bubble, reducing the effects of the bubble pulses. A free surface such as the surface of the sea will repel the bubble which can, in some cases, balance the buoyancy effect and cause the bubble to pulsate at constant depth.

21 The bubble expands and contracts causing high velocities and accelerations of the water in its vicinity. In addition, the velocity with which the bubble rises is very high especially as the bubble collapses. For example, a 136 kg charge of TNT expands to a diameter of 6 m in 0.35 seconds. The average water velocity is about 18 m/s, and the rise velocity is in the region of 30 m/s or more at minimum bubble size. If the bubble of a shallow explosion reaches the surface during the expansion phase it may cause a jet of water to be propelled upward at high velocity to a height of hundreds of metres. Such high velocities of water beneath a ship's hull would penetrate and project a high velocity jet of water into the hull causing further destruction. Except in very large armoured vessels such as battleships no realistic structure can be made sufficiently strong to resist this type of damage.

Resistance to Attack

22 There are two basic philosophies which may be applied to the design of structure for minimum loss of capability after attack. The first is to provide structure to resist and contain the damaging effects, while the second is to allow the damaging mechanisms to be vented outboard while at the same time leaving enough structure to maintain adequate primary strength. The first is the traditional method and includes armouring parts of the ship, while the second is a more recent idea to take account of the very damaging effects of guided missiles with large warheads on medium and small size ships where fitting sufficient armour is impractical. In most cases, however, the solution will be a compromise between the two ideas.

Blast Resistance

23 A ship's structure has, in general, a very complex geometry which gives rise to complicated interactions between the blast waves and the structure. For an accurate and detailed prediction of blast loading it is necessary to conduct model tests, but in the absence of model test data it is possible to make estimates of blast effects on simple geometric shapes such as rectangles and cylinders from which the structure is built up.

24 Plane surfaces exposed to a blast wave at normal incidence are subject to the most severe loads. These loads may be estimated as described in Chapter 4 using a drag coefficient C_D equal to 1.0. Surfaces parallel to the blast direction do not experience a reflected pressure and so the blast load may be found as illustrated in *Figure 4.4* and paragraph 63 of Chapter 4, but with $C_D = -0.4$. The response of cylindrical structures has been the subject of much attention but is becoming of less significance due to the inappropriateness of such structures because of radar signature. Where it is relevant, usually to masts and funnels, the overpressure is of little importance and the dynamic pressure predominates; a value of C_D of 0.75 is usually used.

25 In the case of stiffened panels with relatively low natural frequency (when the natural period is more than four times the positive pressure duration) subject to internal explosions, failure can be predicted from a limiting plate thickness. If the thickness is less than t_{bl} given by equation 15.1 then the plate is likely to fail by plastic membrane action.

$$t_{bl} = KF\,(h/s)\,(p_{qs}/\sigma_y) \tag{15.1}$$

and

$$p_{qs} = 2.25 \times 10^{6}\,(W/V)^{0.72} \tag{15.1a}$$

where K = 2.53×10^{-6} for steel or 3.08×10^{-6} for aluminium
F = $0.6\,\alpha^{-0.6}$ but is not greater than 1.0
α = plate aspect ratio (≤ 1)
h = average distance between decks, bulkheads or deep frames
s = ratio of cross section area of plate plus stiffener to plate alone
p_{qs} = quasi-static overpressure from equation 15.1a
σ_y = yield stress of material

W = TNT equivalent bare weight of charge in kg
V = compartment volume in m^3.

If, however, the panels has a higher natural frequency then failure will be governed by the impulse $\Im$ of the blast wave (that is the area under the pressure-time curve) and the limiting thickness is then given by:

$$t_{bl} = F\,(\Im/s)/\sqrt{(\rho\sigma_y/g)} \tag{15.2}$$

where ρ is the mass density of the material. However $\Im$ is not a parameter which is readily available and advice will need to be sought from specialists when using this equation.

26 These formulae are clearly only of use in specific cases where the size and position of the detonating charge is known. For general purposes there are a number of rules which it is advisable to follow, specifically:

a. Blast will tend to follow a path of least resistance, for example along passageways and through uptake and downtake spaces. It is inadvisable to mount vital equipment on or close to either side of bulkheads lying along potential blast routes or facing doorways opening onto blast routes. The reason for this is that bulkheads, especially corrugated bulkheads, may deflect plastically away from even moderate blast loads and will inflict damage on equipment which would otherwise be largely unaffected.

b. Bulkheads close to the point of detonation may be uprooted and displaced across a compartment. Equipment in the path of such bulkheads will then be destroyed, and so where there is a portion of bulkhead, say at the end of a passageway, which could be severely blast loaded, it is inadvisable to fit vital equipment behind it within that compartment.

c. The implication of bulkhead distortion or displacement on pipe and cable systems must be considered.

d. Watertight doors are unlikely to withstand even moderate blast loading. There is, therefore, a potential benefit in terms of increased survivability to be gained by selecting the direction of door opening in the light of the most likely impact point of an attacking weapon.

e. Long straight passageways extend the region of blast damage. If other design constraints permit, passageways should be broken up into short lengths by some form of 'zig-zag', perhaps for example side passageways moving towards the centre of the ship and then out again. Bulkheads forming the outer edges of corners thus produced should be comparatively rigid and of stiffened flat plate construction and, as stated above, vital equipment should not be fitted in the region of these corners. This passageway configuration also tends to minimise the hazard to personnel caused by displacement by the blast wave of items fitted in the passageway.

f. A bulkhead rivetted around its periphery to a curtain plate has only a quarter to a third of the resistance to blast than a fully welded bulkhead would have. A rivetted bulkhead can, therefore, be used to provide a preferential blast route, but otherwise rivetted arrangements are probably best avoided.

27 Blast transmission is also affected by the ability of the fragment pattern to cut or destroy structure, and blast will demolish structure which has been weakened by fragment penetration. Fragments and blast travel together at a short range from the detonation and so, if there are likely detonation points, it is better in these areas to avoid fitting critical items of equipment rather than to try to strengthen the structure to contain blast. As described earlier, fragments from an exploding weapon tend to be driven forward by the kinetic energy of travel in the form of a hollow cone. Where this cone intersects structure the damage will appear in the form of a line of perforations or even a continuous cut, which not only penetrates plate but also stiffeners. The only means of resisting such damage is to fit some form of armour (thick steel plate or secondary protection such as ceramic tiles) and the additional cost and weight is only likely to be acceptable in regions of high value compartments essential for the continued operation of the ship.

28 This leads on to the second philosophy for retaining operational capability after blast damage, that of providing strong local structure to hold the ship together while weak structure is fitted elsewhere which is quickly destroyed by the blast, allowing it to vent outboard. This is the so-called 'box-girder' style of design which contains a number of strong stiff longitudinal box sections at critical points around the girth and which are connected together by relatively soft structure. A detonation anywhere inside the ship will blow out the soft structure locally, and possibly one box as well, but the remaining box-girders are maintained in their correct spacial relationship by the remaining structure, and especially the main transverse bulkheads which may themselves be of double thickness or box section. The residual strength of the ship after blast damage is calculated to be sufficient for it to return to port in a predefined severe but not extreme sea state. A variety of possible configurations is illustrated in *Figure 15.1*.

29 A box-girder structure was tested in a trial in Germany in 1988 and shown to be highly effective in providing a solution to the blast and fragment problem. However, there are clearly both structure and layout difficulties associated with such an arrangement. To ensure that the ship can resist shear and torsional loads as well as low frequency vibration and fatigue damage, the 'soft' structure still needs to be fairly substantial, both adding to weight which may then be significantly more than for a conventional arrangement, and making it more difficult for the structure to blow out cleanly and dissipate blast energy. Furthermore, internal decks and superstructure interfere with the intended blast paths and the design compromises between soft structure, hard structure and positioning vital equipment become increasingly complex.

30 A possible alternative that might be easier to integrate with a conventional warship arrangement would be to put additional material in critical regions of the cross section, for example in the sheer and deck stringer strakes, bilge strakes or side passageways so as to increase the hull strength well above that required for normal operation. Any loss of structure due to action damage then creates less risk of loss of the ship from structural weakness in bending, although the distribution of structure may be even less effective than the box-girder arrangement in resisting torsional and shear loads.

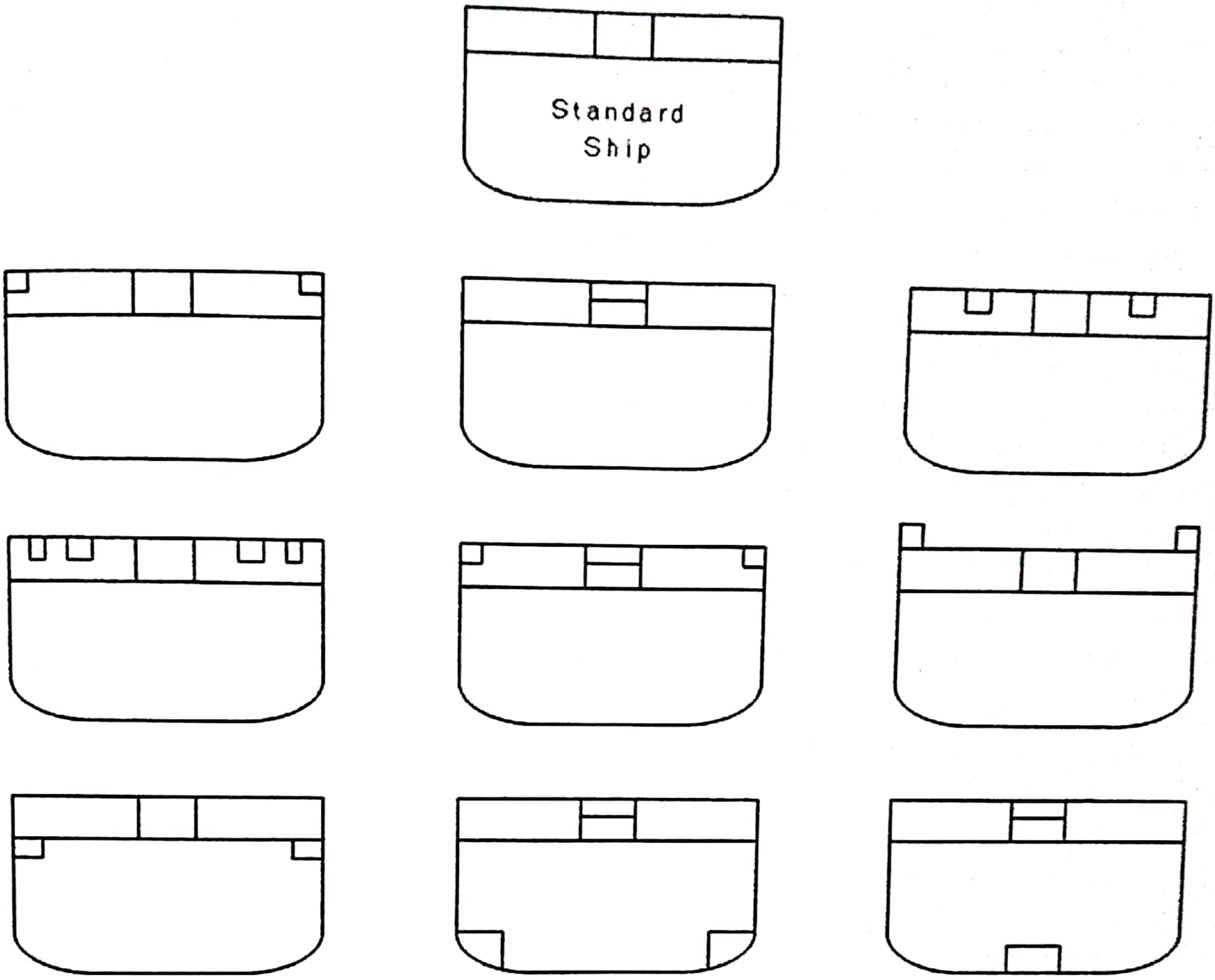

Figure 15.1 Possible Box-Girder Configurations

31 Nevertheless, the advantages of providing residual strength after attack, and providing a means of protecting vital systems within the box-girders, are considered sufficiently attractive to justify further work. In any new warship design the idea of using box-girders over the centre critical length of the ship where the wave loading is greatest, and where the probability of missile impact is also high, should be discussed with structural and vulnerability specialists and the advantages and disadvantages balanced against those of a more conventional arrangement.

Resistance to Shock and Whipping

32 The damaging effects of underwater explosions have been described above. While there is no doubt that heavy scantlings withstand explosive effects better than light scantlings, the experience of WWII afforded many examples of how well lightly constructed ships stood up to damage from non-contact underwater explosions. The thin plating and small stiffeners suffered enormous distortion but with little or no rupture. Heavier structure in larger ships withstood larger explosions but failure was usually by rupture with rather less distortion and so flooding took place relatively earlier.

33 The conclusion that can be drawn from this experience is the importance of attention to detail in the design of hull plating and framing. It is essential to avoid hard spots which can cause stress concentrations and so result in early failure, and special care is needed at right angle junctions of structure, such as decks to ships' side or bulkheads to bottom, to avoid one of the two joining members being unduly stiff and tearing the other member as they absorb energy and distort. The detailed requirements for the connection between main transverse bulkheads and the hull have been discussed in Chapter 9 but the same principles are relevant at all similar connections. It was also clear from WWII experience that it is important to use symmetrical section stiffeners so as to avoid premature tripping and loss of stiffness as the structure distorts.

34 The damage produced by whipping is of a different character from the distortion and tearing of structure caused by the shock and bubble effects. The immediate result of whipping is large amplitude vertical bending of the hull; the first damage resulting from this distortion is usually shear wrinkling in ship's sides near the quarter point lengthwise and in the region of the neutral axis. This is because the shear forces due to whipping are much higher relatively than the bending moments, unlike wave loading effects where bending moment predominates and against which the hull is designed. However, this shear wrinkling is not catastrophic and may not even affect the operational performance provided sea states are not too extreme.

35 The next stage of failure involves compression of the deck and bottom structure, usually resulting in buckling, and either near amidships or in line with the explosion if it is close enough to have weakened the hull girder by direct effects. The actual whipping severity at which the hull will fail is extremely difficult to predict; deck or bottom buckling may not of itself be catastrophic but subsequent cycles of whipping, or later wave loading, may still break the back of the ship. It is possible (see for example Hicks (1986) and Greenhorn (1989)) to predict the vibratory motion of hulls following an underwater explosion with some accuracy provided that the structural response is linear and elastic. The damaging effect is usually presented in the form of whipping contours which effectively relate a particular charge size and stand-off at different positions along the length of the ship to a constant strain level in the upper strength deck as a proportion of the yield strain, as illustrated in *Figure 15.2*.

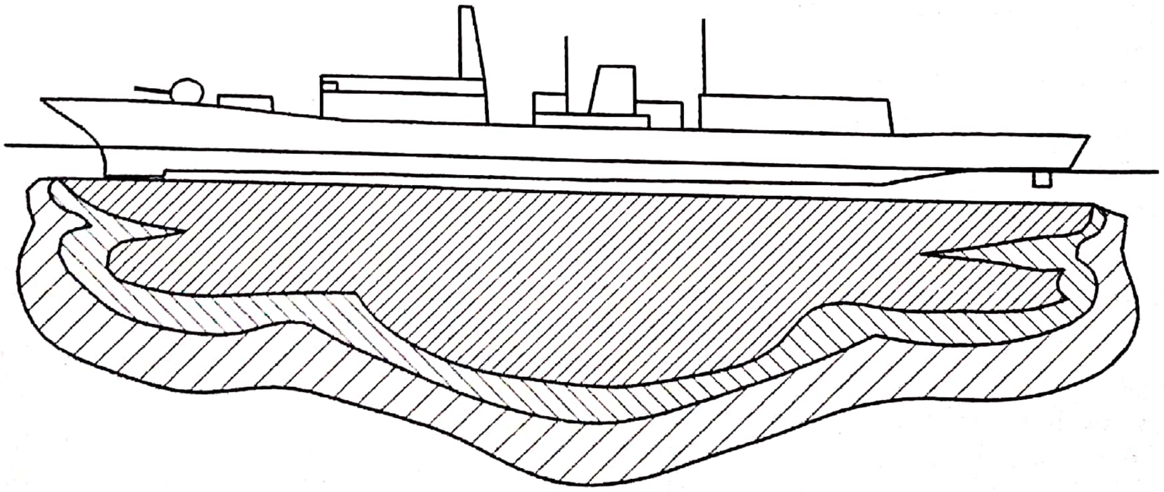

Figure 15.2 Typical Whipping Contours

36 If the structural material has a well defined failure state in compression, such as for fibre reinforced plastic which has no significant post buckling strength, then the procedure constitutes a valuable design check on the conditions which are likely to cause whipping failure, and the stiffness of the hull girder can be improved as required. This is indeed a necessary design condition for mine countermeasures vessels where the charge size and stand-off for normal operations is well defined (see Trimming (1984)). For steel ships where the operational requirement is often ill-defined, and where the actual mode of failure is non-linear and is not directly related to material yield stress, use of the technique remains in the research field; nevertheless, a whipping analysis may yield some insight into the dynamic response of a ship which could help the designer to reduce its vulnerability. It is clear, however, that good structural continuity, emphasised in Chapter 6, is essential for effective resistance to whipping damage. Note that, unlike underwater shock where the charge weight and stand-off can be combined into a single parameter (the shock factor), for whipping both parameters have to be varied independently in any assessment of hull response.

Resistance to Small Arms Attack

37 Bullets from small arms, described in paragraph 5, do not detonate and so the damage resulting from such an attack is limited to kinetic energy effects. If, under the high rates of loading that occur, the structure remains ductile, then a bullet will make a clean hole and pass into the next space with some reduction in velocity. However, most structural materials, including both steel and aluminium, tend to act at least in a partly brittle manner, and so fragments of the structure are often projected along with the bullet.

38 The only realistic methods of protection are to use thick steel, possibly also of greater strength than conventional structural steels, to attach non-structural armour to the face of the structure, or to suspend a secondary surface of material inside to 'catch' the bullet and fragments.

39 The first of these three options is usually the cheapest but also the heaviest, for example to stop a 7.62 mm ball a thickness of at least 20 mm of mild steel is needed. Additionally, more thick material than is necessary for armour protection may have to be fitted to avoid introducing hard spots into the structure which could precipitate early fatigue failure under normal operational loads. Non-structural armour may be in the form of hard metal plates or ceramic tiles which are heavy or expensive and usually both. The other alternative, of a secondary internal surface, may be solid thus forming a sandwich structure, or may be a curtain of material such as woven aramid fibre with a high tensile strength. For either of these there will be fairly complex ship fitting implications and again cost and weight penalties.

40 In modern warships, therefore, it is only likely to be cost effective to fit armour protection to very high value compartments, and even then it may be better to site these compartments well away from the outside of the ship where they are protected by spaces of lesser importance.

Heat Effects

41 Nuclear of fuel-air explosions produce a large heat flux past the structure. For conventional steel upperworks this is not too serious and the worst damage is likely to be charring of paint, although there may be a short duration but sharp rise in the temperature of the steel which could damage equipment, especially cables, attached to it.

42 For fibre reinforced plastic structures the thermal conductivity is so low that the temperature rise in the material will be negligible and no damage will occur to the FRP even though it loses its strength after a relatively small temperature increase (see Chapter 5). Nonetheless, a problem recently discovered with FRP is that at some frequencies it is transparent to the thermal radiation which can then cause unacceptable heating of the inner surface of the structure, possibly damaging screening or other insulating layers. Aluminium, however, both conducts heat well and starts to degrade at about 200°C and so should only be used for critical or high value structures above the waterline if it is absolutely essential for overall design reasons.

Brittle Fracture

43 Finally, and especially if a ship will be expected to be attacked in cold conditions, the requirements for notch tough steel discussed in Chapter 3 must not be forgotten. Any form of explosive attack can precipitate brittle fracture of the structure if the wrong type of steel for the environmental conditions has been used. This is true of ships of all sizes but is perhaps of greatest importance for small vessels required to operate close inshore, likely to suffer mine or bomb attack close to the hull and in temperatures that are nearer to those of the land than the sea.